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STUDY OF THE ADAPTIVE BEAMFORMING DETECTOR USING THE KOREAN SEISMIC RESEARCH STATION SHORT-PERIOD ARRAY

TECHNICAL REPORT NO. 5

VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

Prepared by
Wen-Wu Shen

TEXAS INSTRUMENTS INCORPORATED
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Post Office Box 6015
Dallas, Texas 75222

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Alexandria, Virginia 22314

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Program Code No. 6F10
ARPA Order No. 2551

29 October 1976

Acknowledgment: This research was supported by the Advanced Research Projects Agency, Nuclear Monitoring Research Office, under Project VELA-UNIFORM, and accomplished under the technical direction of the Air Force Technical Applications Center under Contract Number F08606-76-C-0011.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A maximum likelihood constrained time-domain adaptive beamformer was evaluated for its detection performance using short-period data from the Korean Seismic Research Station (KSRS). A total of 132 events in Eurasia was used for the detection study, and two hour-long noise samples were used for false alarm investigation. The results indicated that the present adaptive beamformer yielded practically no increased detection capability from the

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aligned-sum beamformer at the KSRS Short-Period Array, suggesting that the present adaptive beamforming algorithm needs to be improved.

ABSTRACT

A maximum likelihood constrained time-domain adaptive beamformer was evaluated for its detection performance using short-period data from the Korean Seismic Research Station (KSRS). A total of 132 events in Eurasia was used for the detection study, and two hour-long noise samples were used for false alarm investigation. The results indicated that the present adaptive beamformer yielded practically no increased detection capability from the aligned-sum beamformer at the KSRS Short-Period Array, suggesting that the present adaptive beamforming algorithm needs to be improved.

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SECTION I

INTRODUCTION

A. THE ADAPTIVE BEAMFORMING SYSTEM

The adaptive beamforming (ABF) system of Barnard (1974) is a maximum likelihood multichannel time-domain adaptive filtering beamformer. The design goal is to minimize the filter output power subject to unity response constraints in the desired steer direction. The constraints are designed for passing a plane wave signal arriving from the desired steer direction in array beamforming.

The ABF output $y(t)$ is formed by applying a convolution filter to each channel and summing the outputs of all channels:

$$y(t) = \sum_{i=1}^{M} \sum_{j=-N}^{N} a_i(j)\, x_i(t-j)$$

where $a_i(j)$ is the filter weight for the i^{th} channel at a lag of j sample points, $x_i(t-j)$ is the value of the channel i at time $t-j$. M is the number of channels, and $2N+1$ is the total length of the filter in sample points. Prior to forming the filter outputs each channel is time-shifted to time-align energy arriving from the desired steer direction.

The adaptive filter weights $a_i(j)$ are updated by the following algorithm:

$$a_i^{new}(j) = a_i^{old}(j) + \lambda(t)\, y(t) \left[\bar{x}(t-j) - x_i(t-j) \right]$$

where

$$\bar{x}(t-j) = \frac{1}{M} \sum_{i=1}^{M} x_i(t-j)$$

and $\lambda(t)$, which controls the adaptation rate at time t , is computed as follows:

$$\lambda(t) = \frac{\mu}{\sum_{i=1}^{M} \sum_{j=-N}^{N} x_i^2(t-j)} .$$

For this algorithm, μ is the convergence rate discussed in the report and is in general in the range $0 < \mu < 2$. The constraints imposed on the filter weights $a_i(j)$ are:

$$\sum_{i=1}^{M} a_i(j) = \begin{cases} 0 & \text{for } j \neq \text{output point} \\ 1 & \text{for } j = \text{output point.} \end{cases}$$

B. OBJECTIVES

The objectives of this study are as follows:

- To determine the adaptive noise reduction relative to beamsteering and to determine the false alarm probability for the adaptive beamforming detector using short-period data from KSRS.
- To determine the ABF detector's detection performance and to estimate the increased array detection capability by use of the ABF detector.

Section II presents a brief description of the short-period array at the Korean Seismic Research Station and the data base used in this study. Section III presents the results in terms of the false alarm study, detection probability measurements, simulation study, and short-period array response. Major results and conclusions are given in Section IV.

SECTION II
DATA BASE

A. ARRAY

The short-period array at the Korean Seismic Research Station (KSRS) is a 19-element hexagonal array with vertical components. It has an aperture of about 10 km with two rings (for configuration, see Prahl et al., 1975).

B. DATA

Data used in this work were taken from the periods of November 1974 and January and February 1976. Two hour-long noise samples were used for noise reduction and false alarm study. A total of 132 events, 38 of them in central Eurasia (November 1974) and 94 of them in Kurile-Kamchatka (January and February 1976), were used for the detection study.

SECTION III
RESULTS

Subsection A presents noise study and false alarm probability measurements. Subsection B presents the results of detection probability when the ABF was applied to signals. In Subsection C, a simulation study was conducted by burying a scaled signal in noise, followed by array responses in Subsection D.

A. NOISE STUDY AND FALSE ALARM PROBABILITY

Two hour-long noise samples in November 1974 were processed to study the ABF noise reduction relative to beamsteering. In order to find the optimum performance for the ABF, a number of prefilters and two different ABF filter lengths (15 and 31 points) were applied to the single channel data. The prefilters applied were wideband (unfiltered), low frequency passband filter (Figure III-1), array beam optimum detection filter (Figure III-2), single sensor optimum detection filter (Figure III-3), and noise whitening filter (Figure III-4). The filter in Figure III-1 was implemented in the ABF system (originally intended for long-period data), and ABF will default to this filter. The filter in Figure III-2 was designed on the basis of output beam signal and noise spectra to optimize the signal-to-noise ratio for the array beam and therefore is called array beam optimum detection filter. For the same purpose, Figure III-3 was designed from the averaged single-sensor and noise spectra. Finally, the filter in Figure III-4 was designed from noise spectra only to whiten the noise.

Table III-1 shows the processing results from two noise samples (days 312 and 325, 1974). The array steer direction was zero degrees with 15

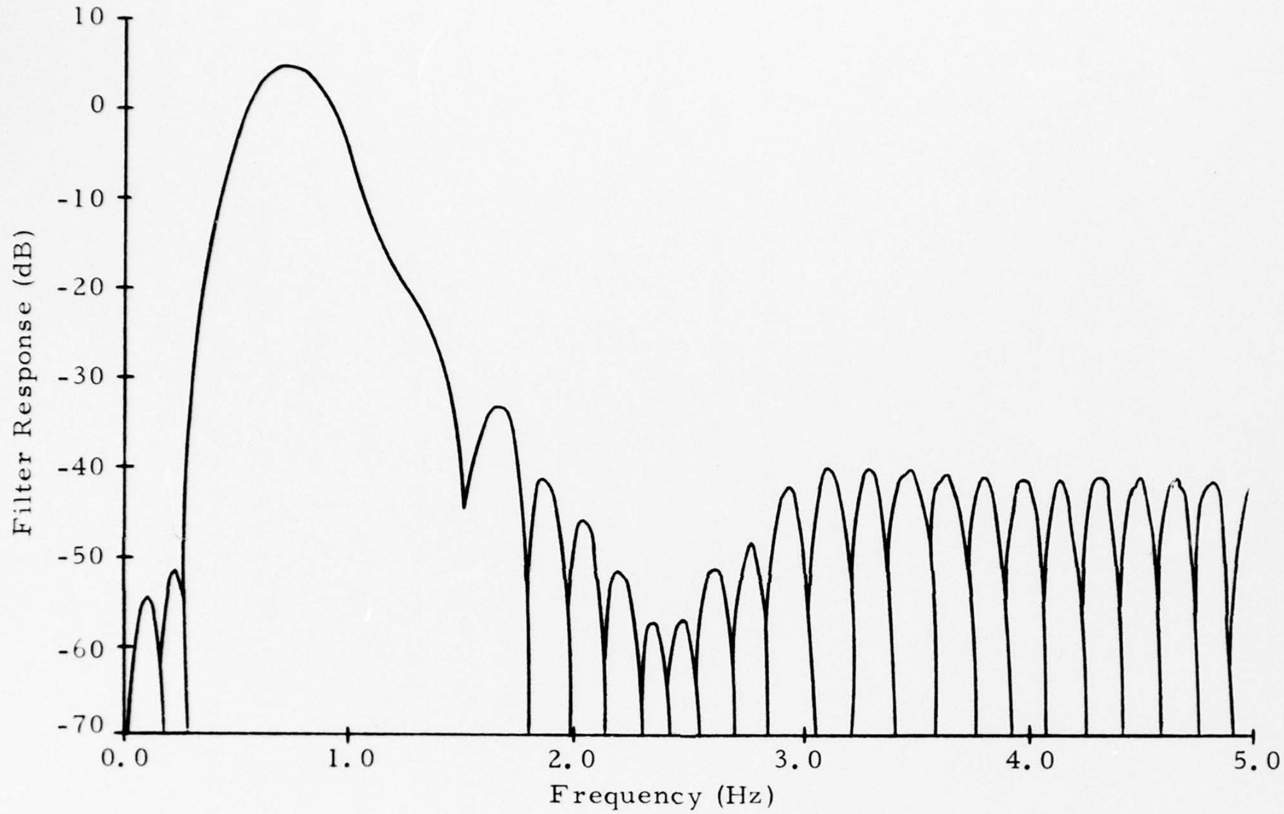


FIGURE III-1

RESPONSES FOR LOW FREQUENCY PASSBAND FILTER

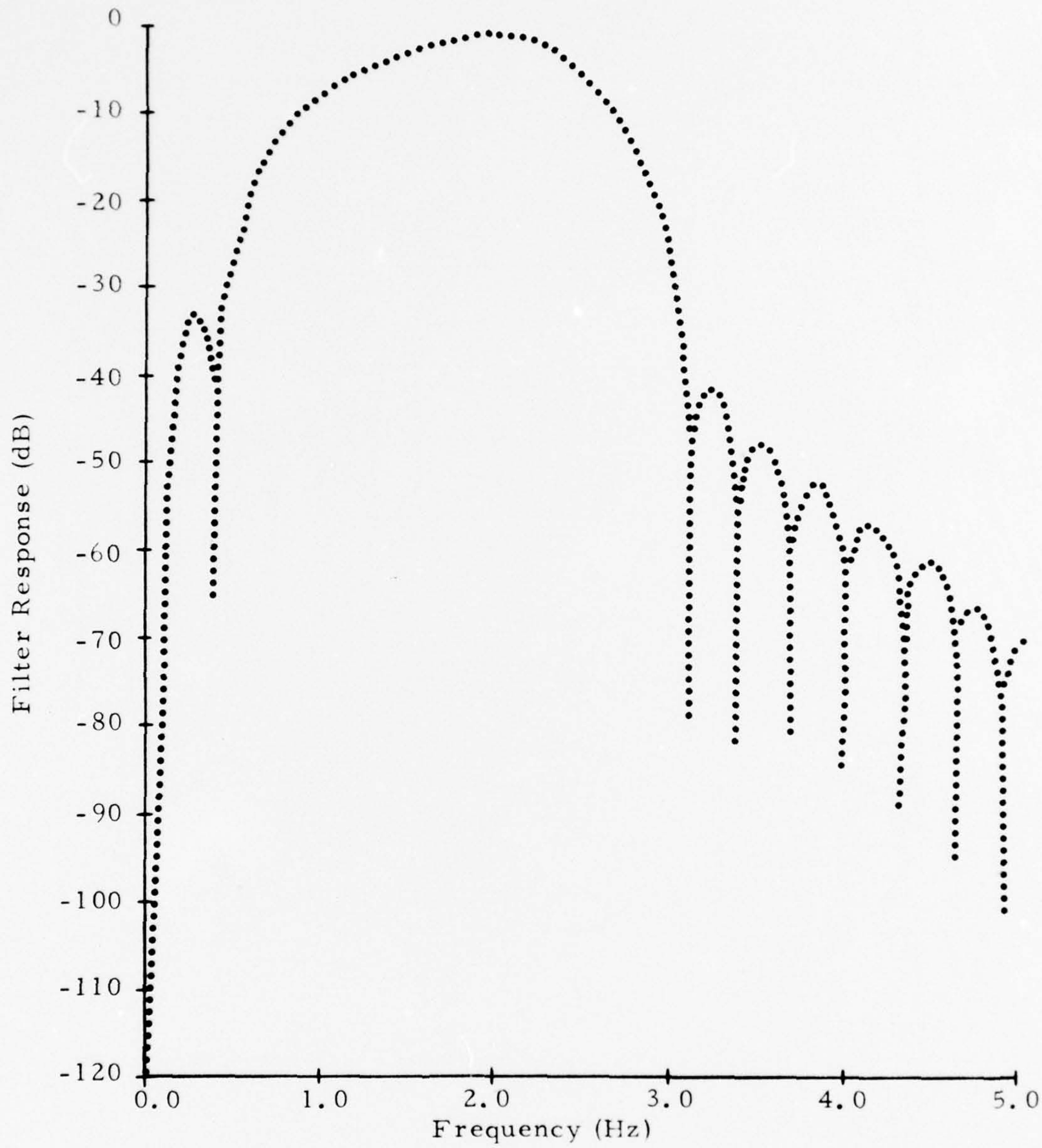


FIGURE III-2

FREQUENCY RESPONSE FOR BEAM OPTIMUM DETECTION FILTER

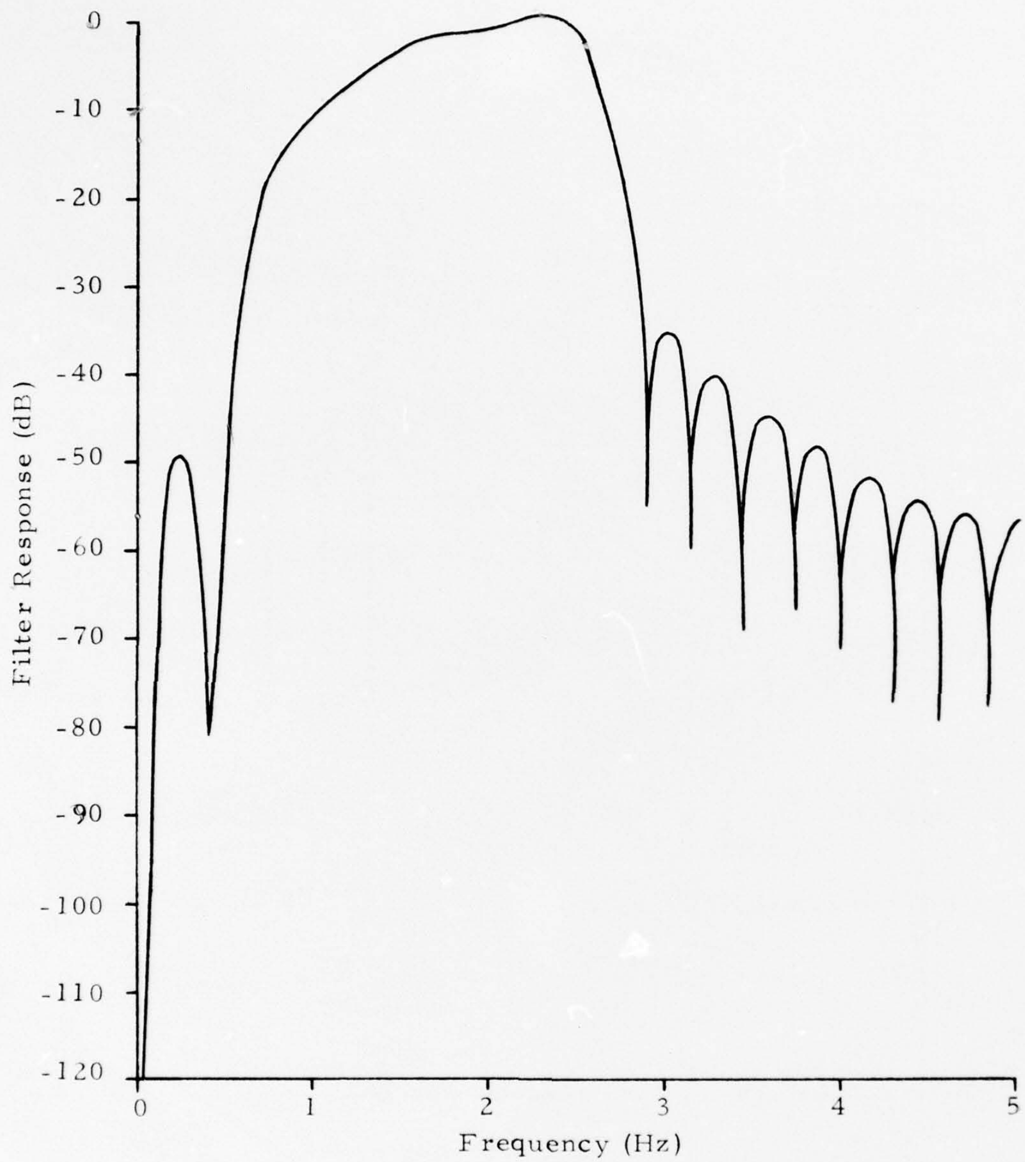


FIGURE III-3

FREQUENCY RESPONSE FOR SINGLE-SENSOR OPTIMUM DETECTION FILTER

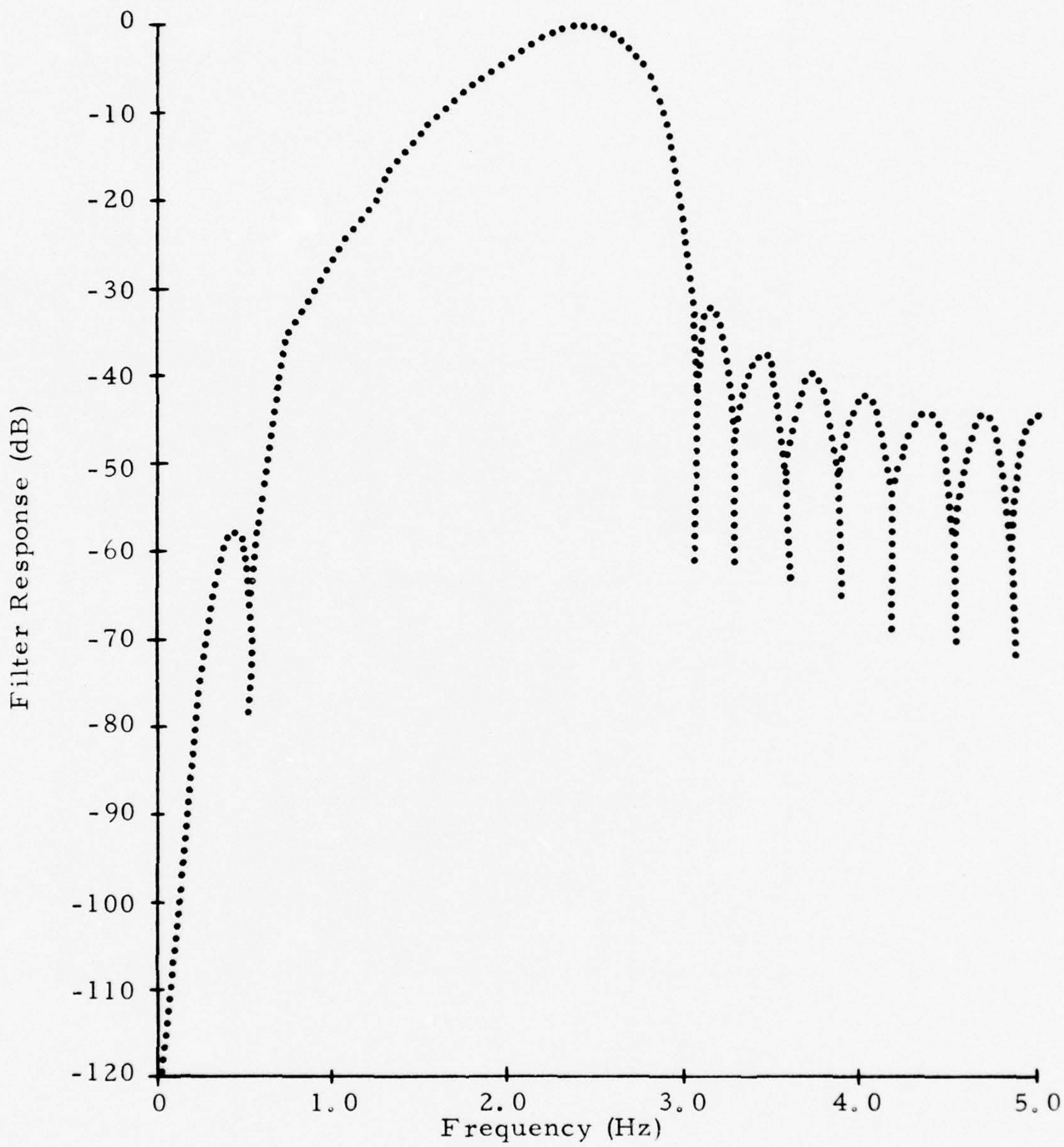


FIGURE III-4

FREQUENCY RESPONSE FOR NOISE WHITENING FILTER

TABLE III-1

ADAPTIVE BEAMFORMER NOISE REDUCTION RELATIVE TO BEAMSTEERING

Noise	ABF Length (points)	Gain (dB)				
		Unfiltered	Low Frequency Passband Filter	Array-Beam Optimum Detection Filter	Single-Sensor Optimum Detection Filter	Whitening Filter
312/15.00.00 to 312/15.57.00	15	6.86	8.44	2.83	2.11	2.93
325/05.05.00 to 325/05.57.00	15	7.14	9.20	3.41	2.51	2.94
312/15.00.00 to 312.15.57.00	31	8.34	8.97	3.26	2.40	3.19
325/15.00.00 to 325/05.57.00	31	9.37	9.69	3.61	2.70	3.27

Numbers in this table are 20 Log_{10} (RMS noise of beamsteer/RMS noise of ABF) decibels.

km per second velocity. The processing gains in the table suggest that the ABF achieved the best noise reduction with the low frequency passband filter, because the low frequency noise is mostly surface wave modes which are better correlated than the noise in higher frequency ranges which are random and compressional modes (Prahl, et al., 1975). Noise spectral analysis (Figure III-5) suggests that the ABF performance decreases as frequency increases.

Noise outputs from the beamsteer and the ABF beams were used for conventional power detector computation. The ratio of the short-term average to the long-term average of these outputs in decibels was formed, where a 30 second sliding window was used for long-term average computation, while various time gates of 0.8, 1.6, 3.2, and 6.4 seconds were used for short-term averages. The mean and standard deviation were computed from these output ratios. Table III-2 and Table III-3 summarize the results of these calculations. It is noteworthy from these results that there is very little difference between beamsteer and ABF results. Also, there is little day-to-day change in the results obtained for the winter noise.

B. DETECTION PROBABILITY MEASUREMENTS

In the following measurements, predicted event azimuth and velocity for beamsteering and ABF were computed from the event locations listed in the Norwegian Seismic Array (NORSAR) bulletin. Signal-to-noise ratios (SNR's) were computed using events with high SNR on single-channel data. The signal-to-noise ratio was the peak-to-peak signal amplitude divided by two-minute RMS noise amplitudes in decibels taken prior to signal arrival. For strong signals, the ABF SNR improvement relative to beamsteering was about 6 to 8 dB using the low frequency passband filter. The improvement was due to noise reduction achieved by the ABF consistent with Table III-1. When the low frequency passband prefilter was applied to the

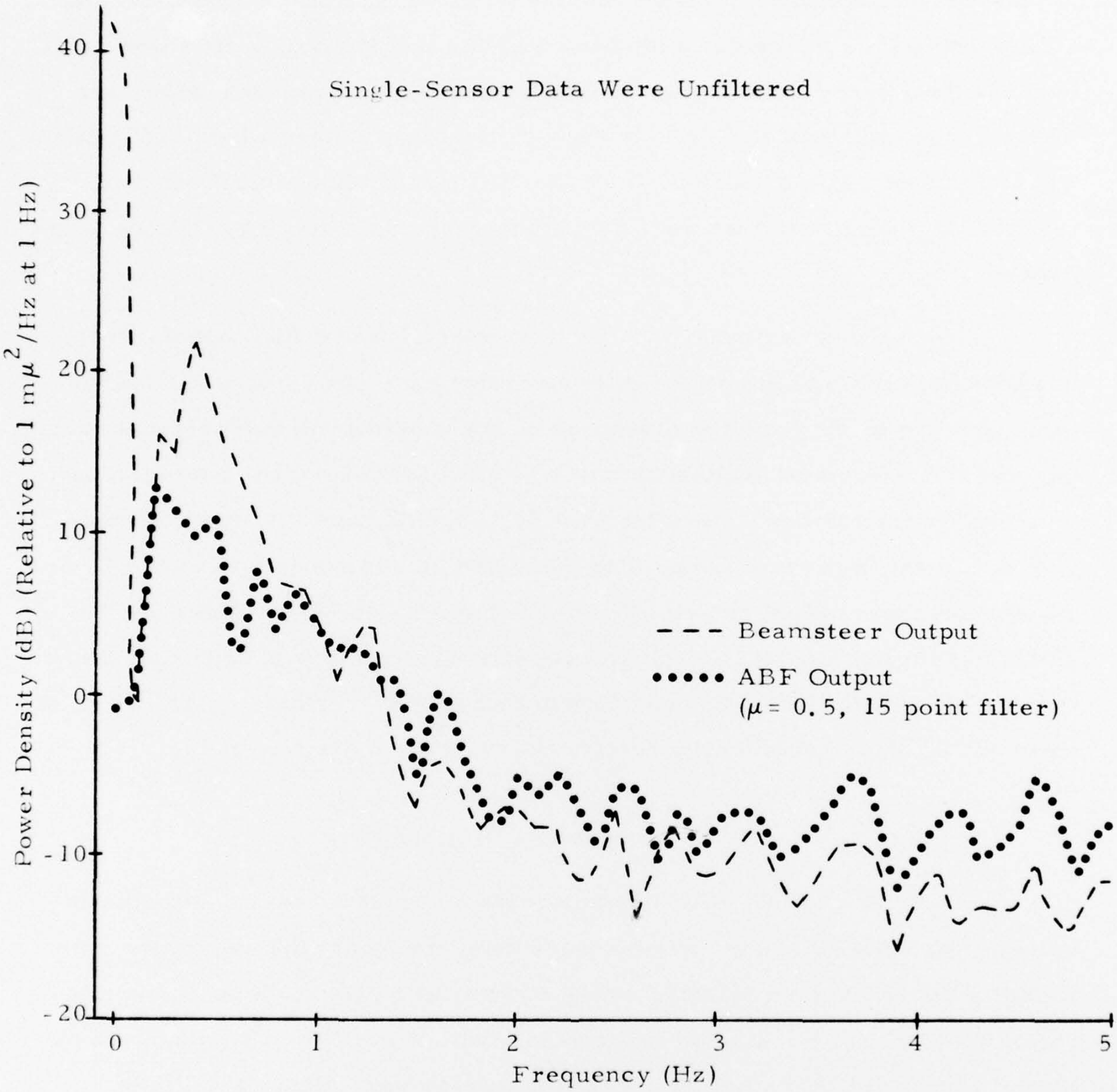


FIGURE III-5

NOISE BEAM SPECTRA FOR DAY 325 1974 SAMPLE
(05.05.00 to 05.18.39)

TABLE III-2

MEAN AND STANDARD DEVIATION FOR ABF AND BEAMSTEER DETECTORS (NOISE SAMPLE: DAY 312 HOUR 15:00 TO 15:57, 1974; 15-POINT ABF LENGTH; 0.5 CONVERGENCE RATE)

Single-Channel Prefilter	Gate (seconds)	Beamsteer Output (dB)		ABF Output (dB)	
		Average (μ)	Standard Deviation (σ)	Average (μ)	Standard Deviation (σ)
Unfiltered	0.8	-2.333	4.948	-1.423	3.747
	1.6	-1.418	3.869	-0.835	2.843
	3.2	-0.703	2.690	-0.493	2.159
	6.4	-0.369	1.915	-0.269	1.606
Single-Sensor Optimum Detection Filter	0.8	-1.322	3.616	-1.246	3.487
	1.6	-0.794	2.736	-0.723	2.604
	3.2	-0.435	2.003	-0.392	1.901
	6.4	-0.218	1.422	-0.197	1.371
Low Frequency Band Filter (0.5-1.1 Hz)	0.8	-2.073	4.770	-1.944	4.600
	1.6	-1.447	3.911	-1.239	3.621
	3.2	-0.838	2.917	-0.685	2.654
	6.4	-0.414	2.014	-0.331	1.842
Array-Beam Optimum Detection Filter	0.8	-1.323	3.635	-1.166	3.391
	1.6	-0.783	2.734	-0.659	2.508
	3.2	-0.417	1.989	-0.350	1.843
	6.4	-0.206	1.403	-0.156	1.286
Whitening Filter	0.8	-1.464	3.777	-1.248	3.500
	1.6	-1.927	2.940	-0.739	2.635
	3.2	-0.552	2.252	-0.420	1.966
	6.4	-0.308	1.699	-0.217	1.442

TABLE III-3

MEAN AND STANDARD DEVIATION FOR ABF AND BEAMSTEER DETECTORS (NOISE SAMPLE: DAY 325 HOUR 05:05 TO 05:57 1974; 15-POINT ABF LENGTH; 0.5 CONVERGENCE RATE)

Single-Channel Prefilter	Gate (seconds)	Beamsteer Output (dB)		ABF Output (dB)	
		Average (μ)	Standard Deviation (σ)	Average (μ)	Standard Deviation (σ)
Unfiltered	0.8	-2.196	4.775	-1.492	3.830
	1.6	-1.313	3.690	-0.875	2.926
	3.2	-0.654	2.529	-0.506	2.210
	6.4	-0.326	1.750	-0.275	1.628
Single-Sensor Optimum Detection Filter	0.8	-1.332	3.630	-1.295	3.593
	1.6	-0.800	2.764	-0.763	2.710
	3.2	-0.442	2.053	-0.418	1.977
	6.4	-0.232	1.496	-0.215	1.428
Low Frequency Band Filter (0.5-1.1 Hz)	0.8	-2.042	4.775	-1.900	4.549
	1.6	-1.433	3.923	-1.228	3.593
	3.2	-0.856	2.995	-0.700	2.697
	6.4	-0.431	2.068	-0.346	1.936
Array-Beam Optimum Detection Filter	0.8	-1.373	3.689	-1.110	3.322
	1.6	-0.817	2.803	-0.624	2.444
	3.2	-0.432	2.036	-0.338	1.796
	6.4	-0.213	1.438	-0.169	1.285
Whitening Filter	0.8	-1.532	3.875	-1.258	3.552
	1.6	-0.991	3.077	-0.742	2.700
	3.2	-0.609	2.420	-0.408	1.998
	6.4	-0.348	1.863	-0.216	1.478

low amplitude signals, the ABF SNR gains degraded to about the beamsteer detection performance.

To estimate roughly the detection capability for the ABF detector, an ensemble of 38 events in the central Eurasian region in November 1974 was processed. Single channel data were examined for all events. Beamforming was performed for those events for which the 'expected' signals were not visible in the single channel data. The criteria for detection was that the peak signal amplitude was at least 1.5 times higher than the peak noise in two minute gates preceding the signal arrival time. Gaussian parameters for detection probability in terms of bodywave magnitude are given in Table III-4. In general, the ABF detector yielded the same detectability as the beamsteer detector.

After receiving the new data from the KSRS array, a total of 94 events in the Kurile-Kamchatka region were processed using the January and February 1976 data. Two convergence rates (0.05 and 0.5) were used with the 15-point filter length and a detection was claimed for the AFB if either or both of the two convergence rate beams yielded a detection. For the low frequency passband, the ABF update was stopped based on apparent SNR output criteria greater than 3 dB.

Figure III-6 presents the least-squares estimate of detection probability for the beamsteer detector (Shen, 1976). The upper part of the figure shows the histogram of detections and the lower part the Gaussian probability curve which indicates a 50 percent detectable bodywave magnitude of 4.12 for the beamsteer detector. The lower magnitude capability for Kurile-Kamchatka as compared with central Eurasia is due to its smaller epicentral distance of 17 degrees. The results in the low frequency passband and in the single-sensor optimum detection passband for the beamsteer and the ABF detectors are presented in Table III-5.

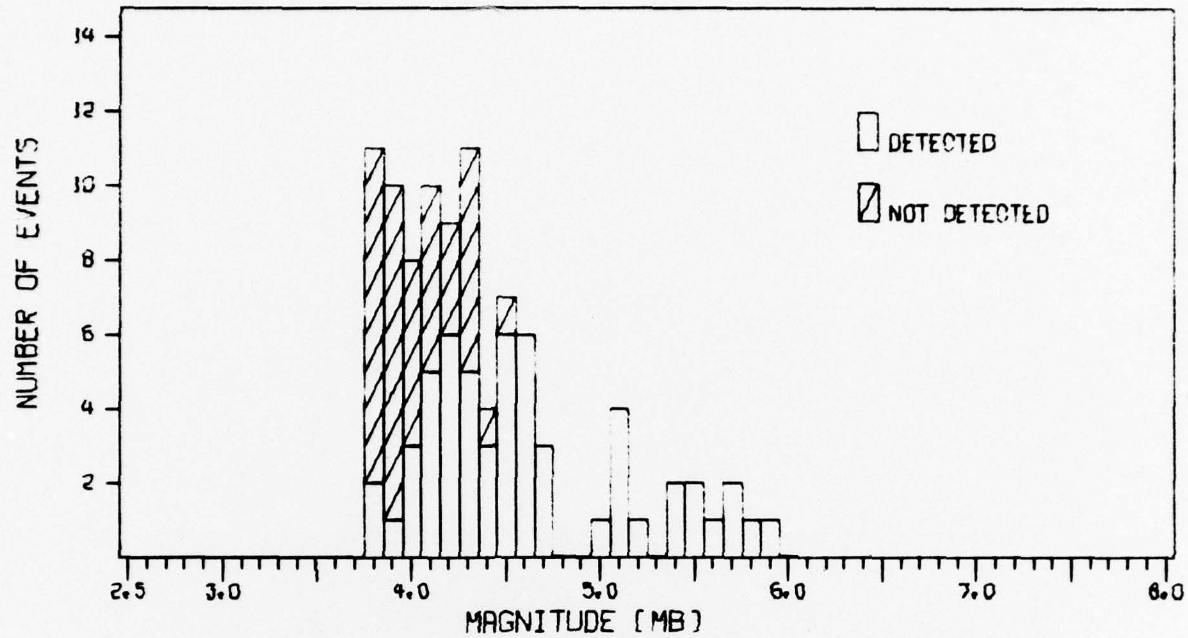
TABLE III-4

MAXIMUM LIKELIHOOD ESTIMATES OF DETECTION PROBABILITIES FOR DELAY-AND-SUM AND ABF BEAMFORMINGS (ON THE BASIS OF 38 EURASIAN EVENTS IN NOVEMBER 1974)

Prefilter	Delay-And-Sum			ABF		
	$m_b 50^{*}$	$m_b 90^{**}$	Standard Deviation σ	$m_b 50^{*}$	$m_b 90^{**}$	Standard Deviation σ
Optimum: Single Sensor (1.5-2.5 Hz)	4.35 ± 0.11	4.90 ± 0.18	0.43 ± 0.11	4.24 ± 0.14	5.01 ± 0.25	0.60 ± 0.19
Optimum: Array Beam (1.0-2.8 Hz)	4.35 ± 0.11	4.90 ± 0.18	0.43 ± 0.11	4.25 ± 0.13	4.93 ± 0.22	0.53 ± 0.16

$^{*}m_b 50$ = 50 percent detectable bodywave magnitude

$^{**}m_b 90$ = 90 percent detectable bodywave magnitude.



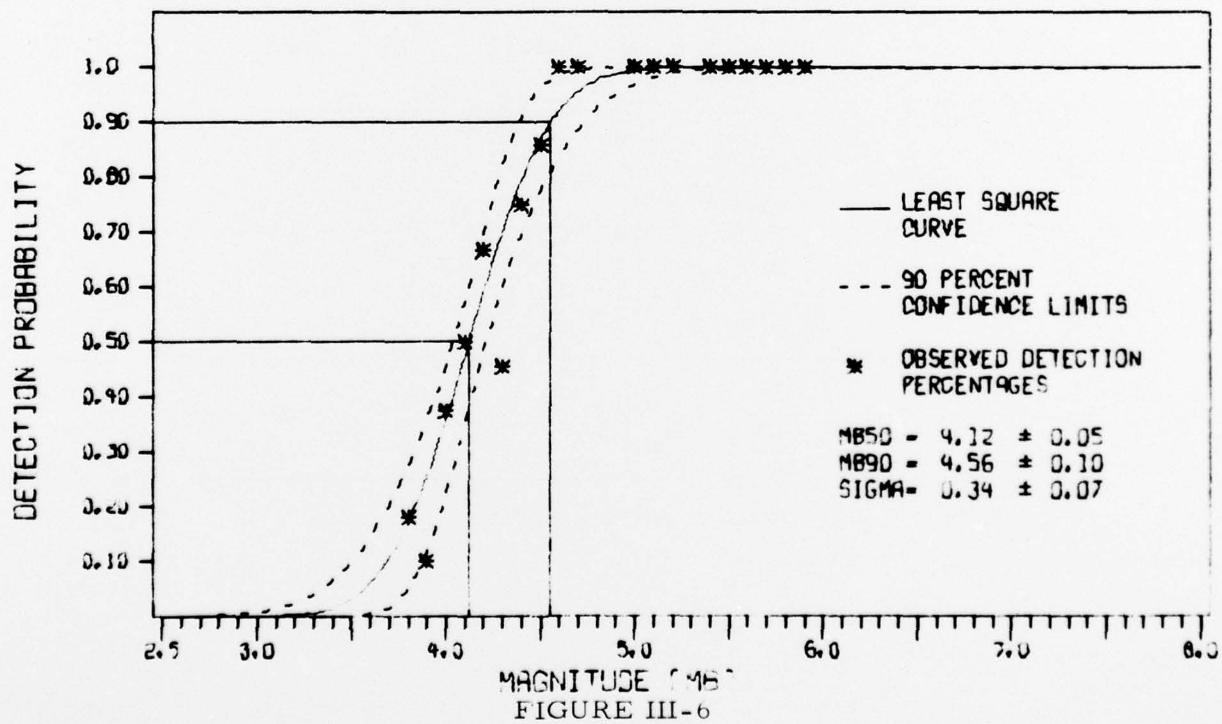


FIGURE III-6

LEAST-SQUARES ESTIMATE OF DETECTION PROBABILITY FOR BEAMSTEERING USING THE SINGLE-SENSOR OPTIMUM FILTER (KURILE-KAMCHATKA, JANUARY AND FEBRUARY 1976)

TABLE III-5

GAUSSIAN PARAMETERS OF DETECTION PROBABILITY FROM LEAST-SQUARES ESTIMATE (KURILE-KAMCHATKA, JANUARY AND FEBRUARY 1976, 94 EVENTS)

Processor	Filter	Mean (μ) 50 Percent Detectable (m_b)	Standard Deviation (σ) (m_b)
ABF	High Frequency Passband*	4.10	0.35
	Low Frequency Passband	4.42	0.68
Beamsteer	High Frequency Passband	4.12	0.34
	Low Frequency Passband	4.54	0.63

* Single-sensor optimum detection filter.

By stopping the ABF update upon the signal-to-noise ratio greater than 3.0 dB, signal degradation decreased somewhat, but false alarms increased considerably. This was due to the fact that with the high convergence rate used in the processing the ABF output amplitude increased immediately as the ABF update was stopped. For the beamsteer detector, the 50 percent detectability was about 0.4 m_b units higher using low frequency passband. For the ABF detector, the difference was about 0.3 m_b units between the two passbands used. The estimates in Table III-5 suggest that there would not be too much improvement in detection capability at the KSRS short-period array by using ABF as compared to beamsteering.

C. SIMULATION STUDY

A simulation study was conducted by burying a scaled signal in noise. This was done by summing two samples, one containing a signal and the other being noise only, in single channel data to form a composite sample from which the ABF was designed. The signal-to-noise ratios for the input signals were varied in the single-sensor level by scaling the signal sample by a factor before adding it to the noise sample. In the simulation, the event from Novaya Zemlya was the signal sample. Fifteen sites (sites 1 to 15) and a 15-point ABF filter length were used. The signal was buried in the noise at various signal-to-noise levels and was processed by both the ABF and beamsteer.

The output signal-to-noise ratios were computed by taking the ratio of signal peak-to-peak amplitude to the RMS noise amplitude two minutes prior to the signal arrival. Figure III-7 shows results using single-sensor optimum detection filter. The ABF SNR gain relative to beamsteering was about 2 dB at high SNR's. This gain degraded to zero at about 15 dB input, a level at which the signal was still easily detectable by beamsteering. Below 15 dB input, this gain was negative.

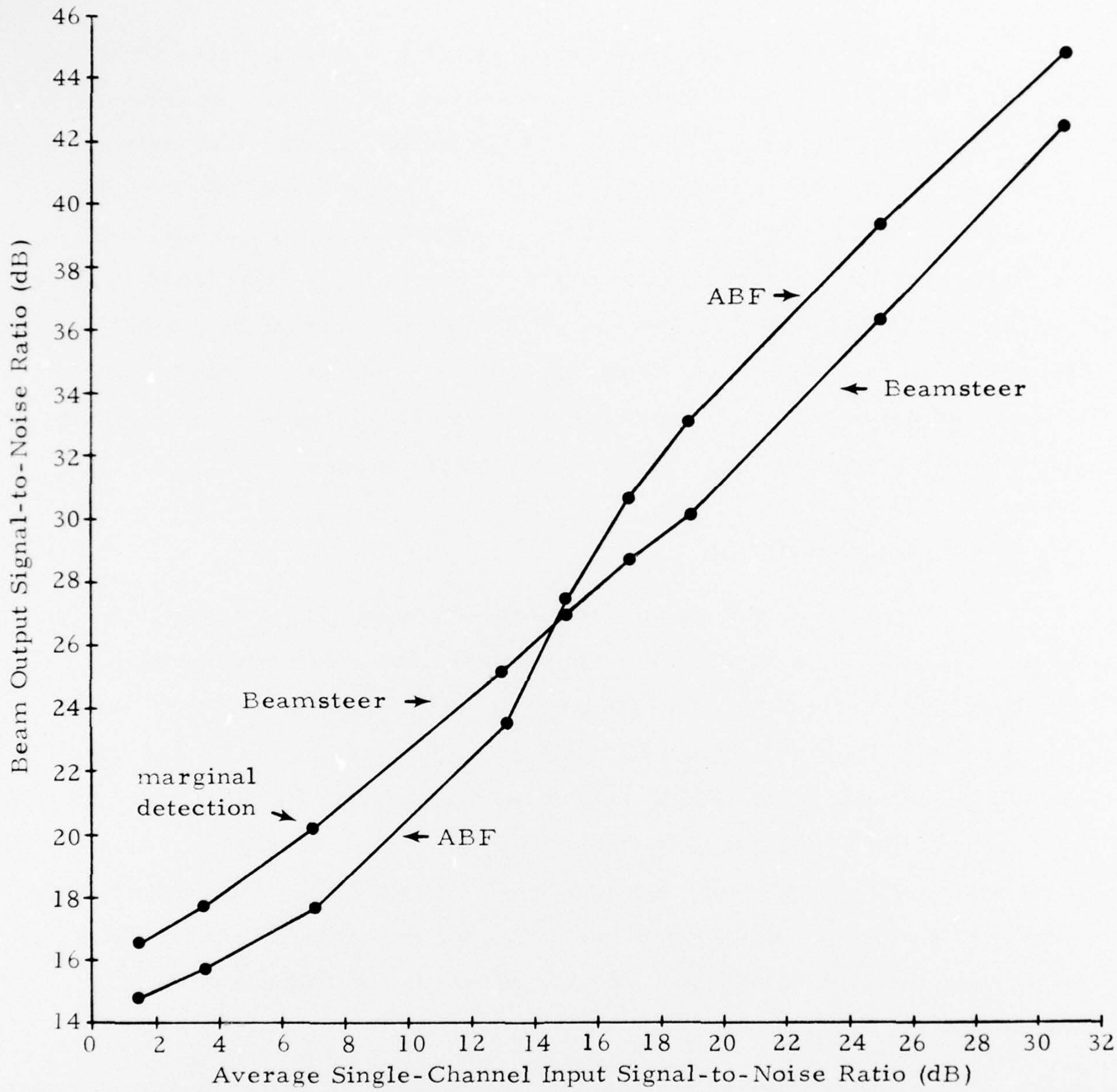


FIGURE III-7

SIMULATION RESULTS USING 15-POINT FILTER, 0.5 CONVERGENCE RATE, AND SINGLE-SENSOR OPTIMUM DETECTION FILTER
(See Figure III-3)

The same simulation was performed using the low frequency passband filter. Figure III-8 presents the results. Two cases were conducted: one with continuous update of the ABF and the other with stopping update of the ABF when the signal-to-noise ratio is greater than 0 dB. For the former case, we essentially obtained the same performance pattern as in Figure III-7. For the latter case, the ABF SNR gain was always greater than the beamsteering.

D. ARRAY RESPONSE

The detector's response pattern for the KSRS short-period data was studied for an event from Greece. The measurements were done by beamforming the event data using various azimuths and velocities. Signal-to-noise ratios were computed by taking the ratio of signal peak-to-peak amplitude to the RMS noise amplitude two minutes prior to the signal arrivals on the beamsteer and the ABF beams, respectively. Figure III-9 shows the response pattern for the beamsteer and the ABF detectors. The dots indicate the source location in velocity-azimuth space. The ABF signal degradation was more pronounced than the beamsteer processor because ABF was not able to take the advantage of signal coherence when the single channels were aligned incorrectly.

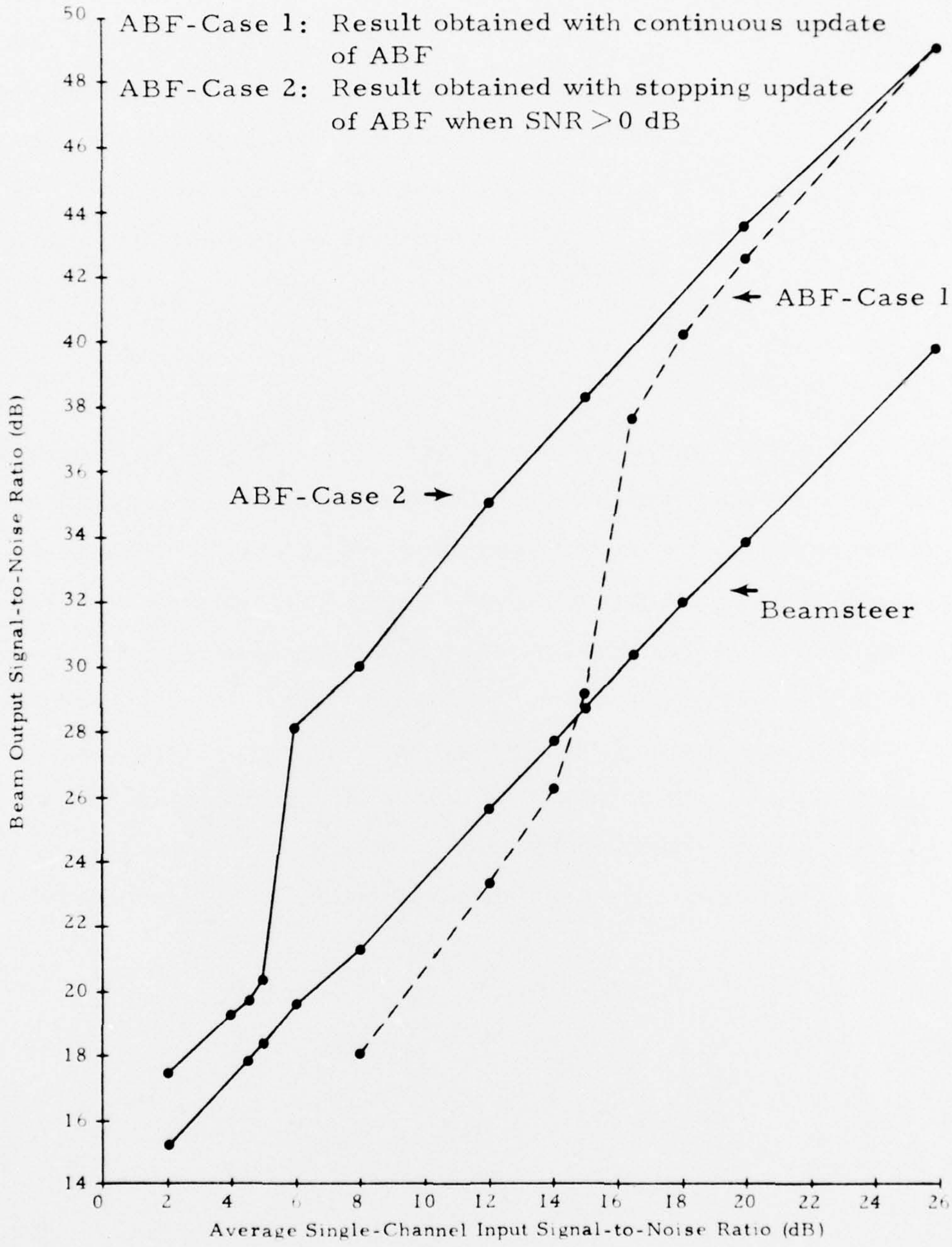


FIGURE III-8

SIMULATION RESULTS USING 15-POINT FILTER, 0.5 CONVERGENCE RATE, AND LOW FREQUENCY PASSBAND FILTER

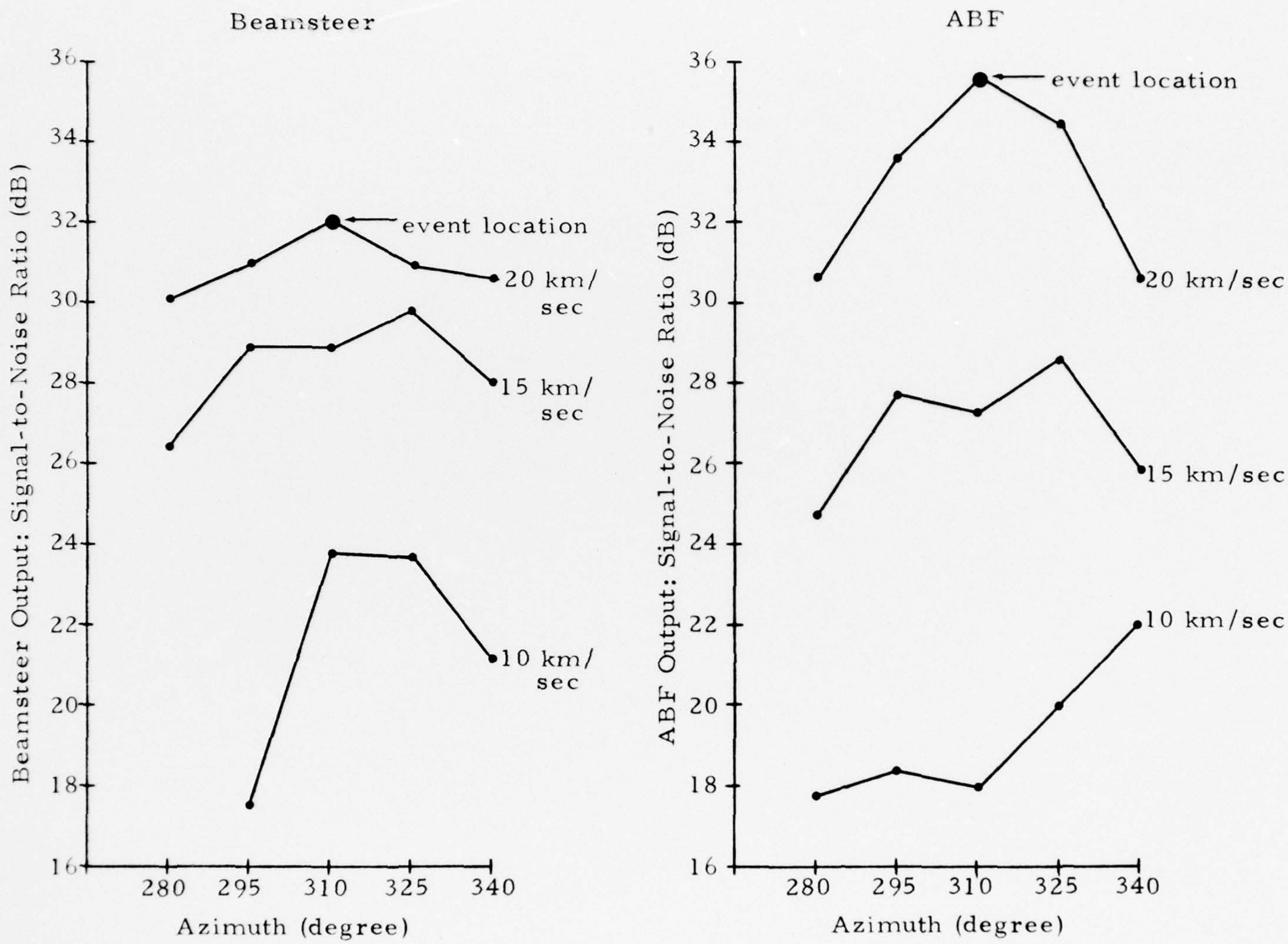


FIGURE III-9

DETECTOR RESPONSE PATTERN FOR KSRS SHORT-PERIOD ARRAY DATA FOR ONE GRECIAN EVENT

SECTION IV
MAJOR RESULTS AND CONCLUSION

The adaptive beamforming detector (ABF) was evaluated for its performance by use of two hour-long noise samples and a total of 132 events in the Eurasian region as recorded at the Korean Seismic Research Station. Major results are presented here.

- For noise reduction, the ABF achieved about a 6 to 10 dB gain relative to beamsteering between 0.5 and 1.1 Hz and a 2 to 4 dB between 1.5 and 2.4 Hz.
- For signal detection, using 38 events from central Eurasia, the detection probability estimate yielded a 50 percent detectable bodywave magnitude of 4.35 m_b for beamsteering and 4.24 m_b for the ABF. For 94 events in Kurile-Kamchatka, the 50 percent detectable bodywave magnitude was 4.12 m_b for beamsteering and 4.10 m_b for the ABF. It is concluded that the ABF provides no improvement over beamsteering for this application.
- A simulation study suggested that signal degradation by the ABF was increased at low input signal-to-noise ratios. Stopping the ABF update when signal-to-noise ratio exceeds certain levels prevented the degradation somewhat at the expense of an increased false alarm rate.

The only conclusion which can be drawn from these results is that the ABF algorithm in its present form as tested here did not yield any advantage over a conventional beamformer for the KSRS short-period data.

SECTION V
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